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Root systems and Clifford algebras: from symmetries of viruses to E_8 and an ADE-like correspondence

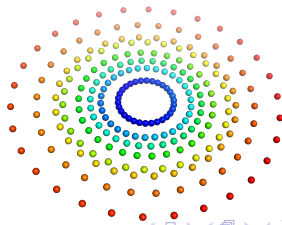
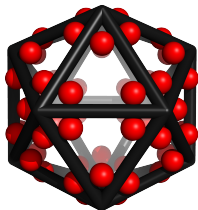
Pierre-Philippe Dechant

Department of Mathematics, University of York

City University – December 6, 2016

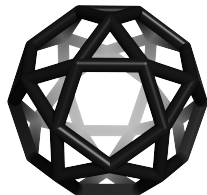
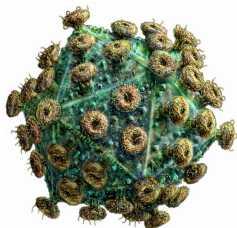
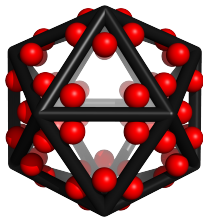
Main results

- New **affine symmetry principle** for viruses and fullerenes
- H_3 (**icosahedral** symmetry) induces the E_8 root system
- Each **3D** root system **induces a 4D** root system
- This **correspondence** extends to exponents in the Coxeter plane (not just the original **Trinity**)
- **Clifford** algebra is a **very natural framework** for root systems and reflection groups



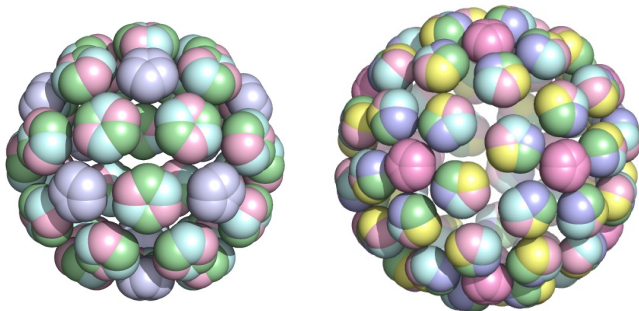
- 1 Viruses, root systems and affine extensions
 - Viruses
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The Icosahedron



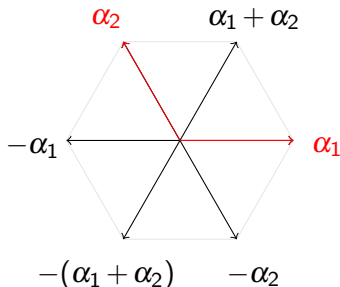
- **Rotational** icosahedral group is $I = A_5$ of order **60**
- **Full** icosahedral group is the **Coxeter group** H_3 of order **120** (including reflections/inversion); generated by the **root system icosidodecahedron**

Icosahedral viruses



Two **viral surface** layouts: a $T = 4$ Caspar-Klug quasiequivalent **triangulation**, and a pseudo $T = 7$ defying Caspar-Klug theory, which is based on a **kite-rhombus** tiling instead (HPV)

Root systems



reflection/Coxeter groups

Root system Φ : set of vectors α in a **vector space** with an **inner product** such that

1. $\Phi \cap \mathbb{R}\alpha = \{-\alpha, \alpha\} \quad \forall \alpha \in \Phi$
2. $s_\alpha \Phi = \Phi \quad \forall \alpha \in \Phi$

Simple roots: express every element of Φ via a **\mathbb{Z} -linear combination**.

$$s_\alpha : v \rightarrow s_\alpha(v) = v - 2 \frac{(v|\alpha)}{(\alpha|\alpha)} \alpha$$

Cartan Matrices

Cartan matrix of α_i s is $A_{ij} = 2 \frac{(\alpha_i | \alpha_j)}{(\alpha_i | \alpha_i)} = 2 \frac{|\alpha_j|}{|\alpha_i|} \cos \theta_{ij}$

$$A_2: A = \begin{pmatrix} 2 & -1 \\ -1 & 2 \end{pmatrix}$$

Coxeter-Dynkin diagrams: node = simple root, no link = roots orthogonal, simple link = roots at $\frac{\pi}{3}$, link with label m = angle $\frac{\pi}{m}$.

$$A_3 \circ - \circ - \circ$$

$$B_3 \circ - \overset{4}{\circ} - \circ$$

$$H_3 \circ - \overset{5}{\circ} - \circ$$

$$I_2(n) \circ - \overset{n}{\circ}$$

Lie groups to Lie algebras to Coxeter groups to root systems

- **Lie group**: manifold of continuous symmetries (gauge theories, spacetime)
- **Lie algebra**: infinitesimal version near the identity
- Non-trivial part is given by a **root lattice**
- **Weyl** group is a **crystallographic** Coxeter group:
 $A_n, B_n/C_n, D_n, G_2, F_4, E_6, E_7, E_8$ generated by a **root system**.
- So via this route root systems are **always** crystallographic.
Neglect non-crystallographic root systems $I_2(n), H_3, H_4$.

Affine extensions

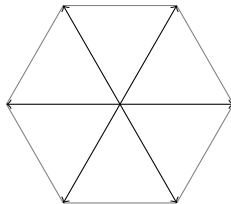
An **affine Coxeter group** is the extension of a Coxeter group by an **affine reflection in a hyperplane not containing the origin** $s_{\alpha_0}^{aff}$ whose geometric action is given by

$$s_{\alpha_0}^{aff} v = \alpha_0 + v - \frac{2(\alpha_0 | v)}{(\alpha_0 | \alpha_0)} \alpha_0$$

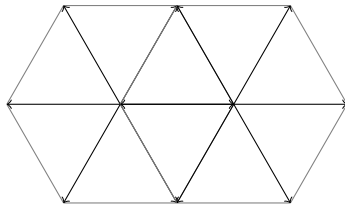
Non-distance preserving: includes the **translation generator**

$$T v = v + \alpha_0 = s_{\alpha_0}^{aff} s_{\alpha_0} v$$

Affine extensions – A_2

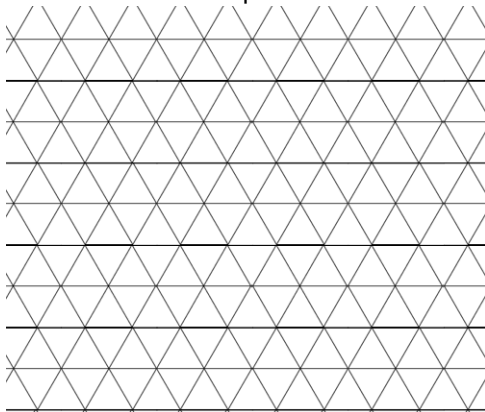


Affine extensions – A_2

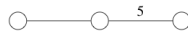
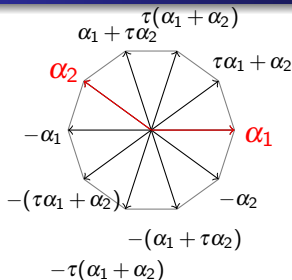


Affine extensions – A_2

Affine extensions of crystallographic Coxeter groups lead to a **tessellation** of the plane and a **lattice**.



Non-crystallographic Coxeter groups $H_2 \subset H_3 \subset H_4$



$$A = \begin{pmatrix} 2 & -\tau \\ -\tau & 2 \end{pmatrix}$$

$$A = \begin{pmatrix} 2 & -1 & 0 \\ -1 & 2 & -\tau \\ 0 & -\tau & 2 \end{pmatrix}$$

$$A = \begin{pmatrix} 2 & -1 & 0 & 0 \\ -1 & 2 & -1 & 0 \\ 0 & -1 & 2 & -\tau \\ 0 & 0 & -\tau & 2 \end{pmatrix}$$

$H_2 \subset H_3 \subset H_4$: 10, 120, 14,400 elements, the only Coxeter groups that generate **rotational symmetries of order 5** linear combinations now in the **extended integer ring**

$$\mathbb{Z}[\tau] = \{a + \tau b \mid a, b \in \mathbb{Z}\} \quad \text{golden ratio}$$

$$\tau = \frac{1}{2}(1 + \sqrt{5}) = 2 \cos \frac{\pi}{5}$$

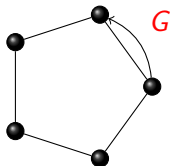
$$x^2 = x + 1$$

$$\tau' = \sigma = \frac{1}{2}(1 - \sqrt{5}) = 2 \cos \frac{2\pi}{5}$$

$$\tau + \sigma = 1, \tau\sigma = -1$$

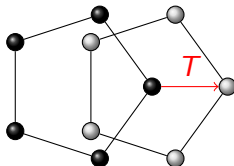
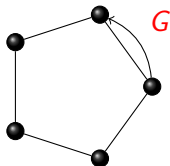
Affine extensions of non-crystallographic root systems?

Unit translation along a vertex of a unit pentagon



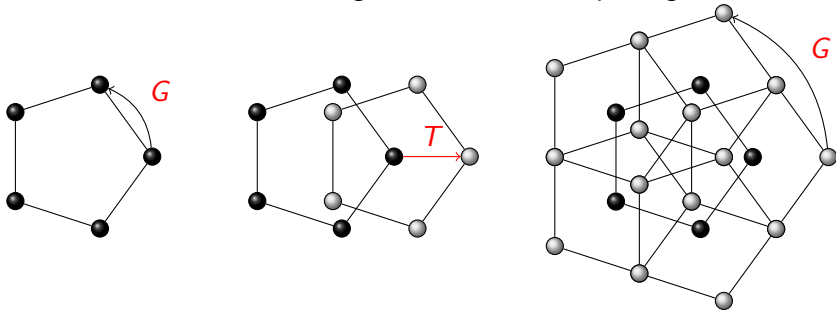
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Affine extensions of non-crystallographic root systems?

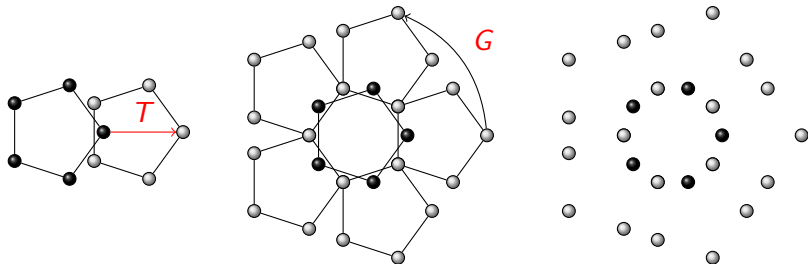
Unit translation along a vertex of a unit pentagon



A **random** translation would give 5 secondary pentagons, i.e. 25 points. Here we have **degeneracies** due to 'coinciding points'.

Affine extensions of non-crystallographic root systems?

Translation of length $\tau = \frac{1}{2}(1 + \sqrt{5}) \approx 1.618$ (golden ratio)

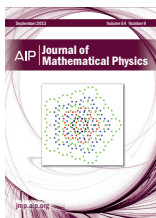


Cartoon version of a **virus** or **carbon onion**. Would there be an **evolutionary benefit** to have more than just compact symmetry?

The problem has an **intrinsic length scale**.

Affine extensions of non-crystallographic Coxeter groups

- 2D and 3D **point arrays** for applications to viruses, fullerenes, quasicrystals etc
- **Two complementary ways** to construct these



Know your onions

Acta Cryst. A 70, 162-167 (2014)

Many viruses have icosahedral symmetry. So do certain 'carbon onions' — Russian doll-like arrangements of nested fullerenes. Pierre-Philippe Dechant and colleagues argue that viruses and carbon onions share the same formation principle: affine symmetry. Imagine a set of points lying on the vertices of a regular pentagon. Duplicate the set, and translate it, then repeatedly rotate the combined set over 72° about the midpoint of the original pentagon. This results in a new set of points obeying five-fold symmetry, yet with a 2D shell structure that is more complex than that of the pentagon. A similar 'affinization' of the 3D icosahedral group results in a set of points that are nodes in the highly complex protein network structure of, for example, the Penicillium virus.

Dechant *et al.* found that affine symmetry explains the structure of experimentally observed carbon onions — a non-trivial result given that all carbon atoms in each of the nested fullerene molecules must be three-connected, that is, bound to three neighbouring carbons. In particular, they identified the extended group that, starting from buckminsterfullerene (the 'buckyball'), generates the onion $C_{60}@C_{60}@C_{60}$.

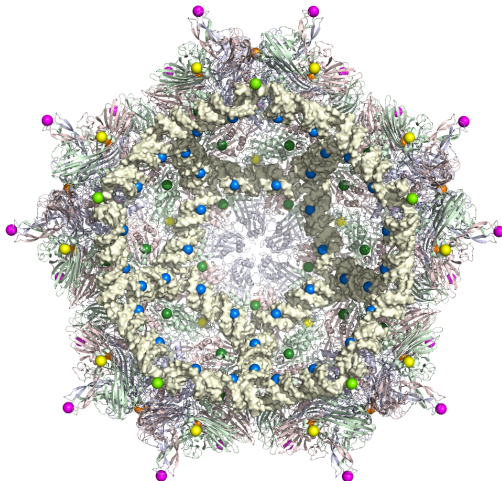
well known effect for photons, and it turns out to hold for other quantum particles too. James Fokas and colleagues have performed the Hong–Ou–Mandel quantum interference experiment using plasmons, which are quantized surface plasma waves. Pairs of photons are fed into a specially designed plasmonic waveguide that mixes the paths of the light-excited surface plasmons in the same way as a beam splitter. The outcome is connected back into photons and measured by two detectors. As in the purely photonic case, the characteristic dip in coincidence rate is shown, showing that the photons remain indistinguishable when they are converted into plasmons and interfere.

Written by May Chiao, Miki Georgiou, Abigail Kopper, Bart Verbrink and Adam Wright

NATURE PHYSICS | VOL 10 | APRIL 2014 | www.nature.com/naturephysics

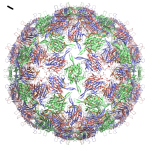
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Use in Mathematical Virology



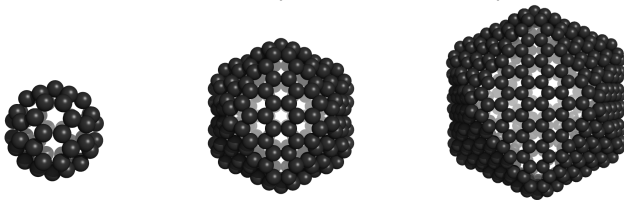
New insight into RNA virus assembly

- There are **specific interactions** between **RNA** and coat protein (**CP**) given by **symmetry** axes
- Essential for **assembly** as only this RNA-CP interaction turns CP into **right geometric** shape for **capsid formation**
- The RNA forms a **Hamiltonian cycle** visiting each CP once – dictated by symmetry
- A **patent** for a new antiviral strategy (Reidun Twarock)



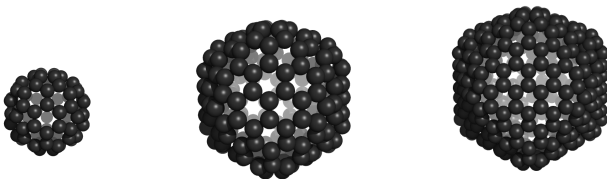
Extension to fullerenes: carbon onions

- Extend idea of affine symmetry to other icosahedral objects in nature: football-shaped **fullerenes**
- Recover different shells with icosahedral symmetry from affine approach: **carbon onions** ($C_{60} - C_{240} - C_{540}$)



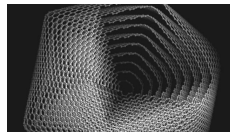
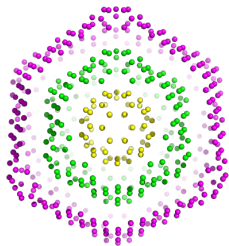
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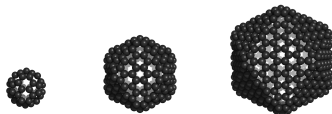
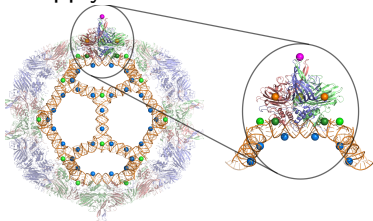
Viruses and fullerenes – symmetry as a common thread?

- Get nested arrangements like Russian dolls: **carbon onions** (e.g. Nature 510, 250253)
- Potential to extend to **other known carbon onions** with different start configuration, chirality etc



Two major areas for affine extensions of non-crystallographic Coxeter groups

- Non-compact symmetry that relates **different structural features** in the same polyhedral object
- **Novel symmetry principle** in Nature, shown that it seems to apply to at least **fullerenes** and **viruses**



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Clifford Algebra and orthogonal transformations

- Form an algebra using the product between two vectors

$$ab \equiv a \cdot b + a \wedge b$$

- Inner product** is symmetric part $a \cdot b = \frac{1}{2}(ab + ba)$
- Reflecting x in n is given by $x' = x - 2(x \cdot n)n = -n x n$ (n and $-n$ **doubly cover** the same reflection)
- Via **Cartan-Dieudonné** theorem any orthogonal (/conformal/modular) transformation can be written as **successive reflections**

$$x' = \pm n_1 n_2 \dots n_k x n_k \dots n_2 n_1 = \pm A x \tilde{A}$$

Clifford Algebra of 3D

- E.g. **Pauli algebra** in 3D (likewise for **Dirac algebra** in 4D) is

$$\underbrace{\{1\}}_{1 \text{ scalar}} \quad \underbrace{\{e_1, e_2, e_3\}}_{3 \text{ vectors}} \quad \underbrace{\{e_1 e_2, e_2 e_3, e_3 e_1\}}_{3 \text{ bivectors}} \quad \underbrace{\{I \equiv e_1 e_2 e_3\}}_{1 \text{ trivector}}$$

- We can **multiply together root vectors** in this algebra $\alpha_i \alpha_j \dots$
- A general element has **8** components, **even** products (rotations/spinors) have **four** components:

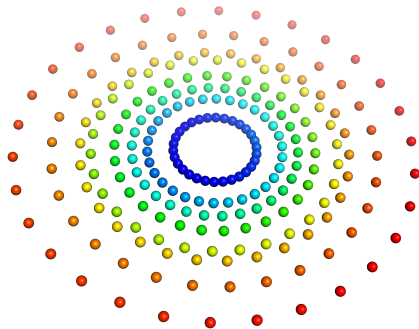
$$R = a_0 + a_1 e_2 e_3 + a_2 e_3 e_1 + a_3 e_1 e_2 \Rightarrow R \tilde{R} = a_0^2 + a_1^2 + a_2^2 + a_3^2$$

- So behaves as a **4D Euclidean** object – inner product

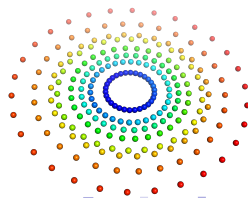
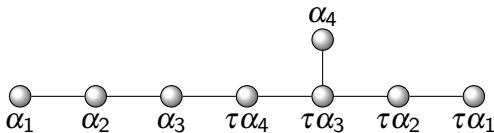
$$(R_1, R_2) = \frac{1}{2}(R_2 \tilde{R}_1 + R_1 \tilde{R}_2)$$

Exceptional E_8 (projected into the Coxeter plane)

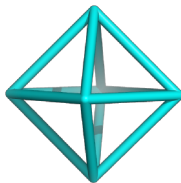
E_8 root system has 240 roots, H_3 has order 120



- Order 120 group H_3 doubly covered by **240 (s)pinors** in 8D space
- With (somewhat counterintuitive) **reduced inner product** this gives the E_8 root system
- **E_8 is actually hidden within 3D geometry!**



Spinors from reflections



- The 6 **roots** $(\pm 1, 0, 0)$ and permutations of $A_1 \times A_1 \times A_1$ generate 8 **spinors**:
- $\boxed{\pm e_1, \pm e_2, \pm e_3}$ give the 8 spinors $\boxed{\pm 1, \pm e_1 e_2, \pm e_2 e_3, \pm e_3 e_1}$
- This is a **discrete spinor group** isomorphic to the **quaternion** group Q .
- As **4D vectors** these are $(\pm 1, 0, 0, 0)$ and permutations, the 8 **roots** of $A_1 \times A_1 \times A_1 \times A_1$ (the 16-cell).

Induction Theorem – root systems

- Induction Theorem: every 3D root system gives a 3D spinor group which gives a 4D root system.

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Induction Theorem – root systems

- Induction Theorem: every 3D root system gives a 3D spinor group which gives a 4D root system.
- Check axioms:
 1. $\Phi \cap \mathbb{R}\alpha = \{-\alpha, \alpha\} \quad \forall \alpha \in \Phi$
 2. $s_\alpha \Phi = \Phi \quad \forall \alpha \in \Phi$
- Proof: 1. R and $-R$ are in a spinor group by construction (double cover of orthogonal transformations), 2. closure under reflections is guaranteed by the closure property of the spinor group (with a twist: $-R_1 \tilde{R}_2 R_1$)

H_4 from H_3

- The H_3 root system has 30 **roots** e.g. simple roots

$$\alpha_1 = e_2, \alpha_2 = -\frac{1}{2}((\tau-1)e_1 + e_2 + \tau e_3) \text{ and } \alpha_3 = e_3.$$

- Subgroup of **rotations** A_5 of order **60** is doubly covered by **120**

spinors of the form $\alpha_1 \alpha_2 = -\frac{1}{2}(1 - (\tau-1)e_1 e_2 + \tau e_2 e_3),$

$\alpha_1 \alpha_3 = e_2 e_3$ and $\alpha_2 \alpha_3 = -\frac{1}{2}(\tau - (\tau-1)e_3 e_1 + e_2 e_3).$

•

$$(\pm 1, 0, 0, 0) \text{ (8 perms)}, \frac{1}{2}(\pm 1, \pm 1, \pm 1, \pm 1) \text{ (16 perms)}$$

$$\frac{1}{2}(0, \pm 1, \pm \sigma, \pm \tau) \text{ (96 even perms),}$$

As **4D vectors** are the 120 roots of the **H_4 root system**.

Spinors from reflections

- The 3D Coxeter groups that are symmetry groups of the **Platonic Solids**:
- The 6/12/18/30 **roots** in $A_1 \times A_1 \times A_1 / A_3 / B_3 / H_3$ generate 8/24/48/120 **spinors**.
- E.g. $\pm e_1, \pm e_2, \pm e_3$ give the 8 spinors $\pm 1, \pm e_1 e_2, \pm e_2 e_3, \pm e_3 e_1$
- The **discrete spinor group** is isomorphic to the **quaternion group** Q / **binary tetrahedral group** $2T$ / **binary octahedral group** $2O$ / **binary icosahedral group** $2I$).

A_1^3	A_3	B_3	H_3
A_1^4	D_4	F_4	H_4

Exceptional Root Systems

- **Exceptional** phenomena: D_4 (**triality**, important in string theory), F_4 (**largest lattice symmetry** in 4D), H_4 (**largest non-crystallographic symmetry**); **Exceptional** D_4 and F_4 arise from **series** A_3 and B_3

rank-3 group	diagram	binary	rank-4 group	diagram
$A_1 \times A_1 \times A_1$		Q	$A_1 \times A_1 \times A_1 \times A_1$	
A_3		$2T$	D_4	
B_3		$2O$	F_4	
H_3		$2I$	H_4	

Arnold's Trinities

Arnold's observation that many areas of real mathematics can be **complexified** and **quaternionified** resulting in theories with a similar structure.

- The **fundamental trinity** is thus $(\mathbb{R}, \mathbb{C}, \mathbb{H})$
- The **projective spaces** $(\mathbb{R}P^n, \mathbb{C}P^n, \mathbb{H}P^n)$
- The **spheres** $(\mathbb{R}P^1 = S^1, \mathbb{C}P^1 = S^2, \mathbb{H}P^1 = S^4)$
- The **Möbius/Hopf bundles** $(S^1 \rightarrow S^1, S^4 \rightarrow S^2, S^7 \rightarrow S^4)$
- The **Lie Algebras** (E_6, E_7, E_8)
- The symmetries of the **Platonic Solids** (A_3, B_3, H_3)
- The **4D groups** (D_4, F_4, H_4)
- **New connections** via my **Clifford spinor construction** (see McKay correspondence)

Platonic Trinities

- Arnold's connection between (A_3, B_3, H_3) and (D_4, F_4, H_4) is **very convoluted** and involves numerous other trinities at intermediate steps:
- **Decomposition of the projective plane** into Weyl chambers and Springer cones
- The **number of Weyl chambers** in each segment is $24 = 2(1 + 3 + 3 + 5)$, $48 = 2(1 + 5 + 7 + 11)$, $120 = 2(1 + 11 + 19 + 29)$
- Notice this miraculously **is one less than the degrees of invariants** $((2, 4, 4, 6), (2, 6, 8, 12), (2, 12, 20, 30))$ of the Coxeter groups (D_4, F_4, H_4)
- Believe the Clifford connection is **more direct**

A unified framework for polyhedral groups

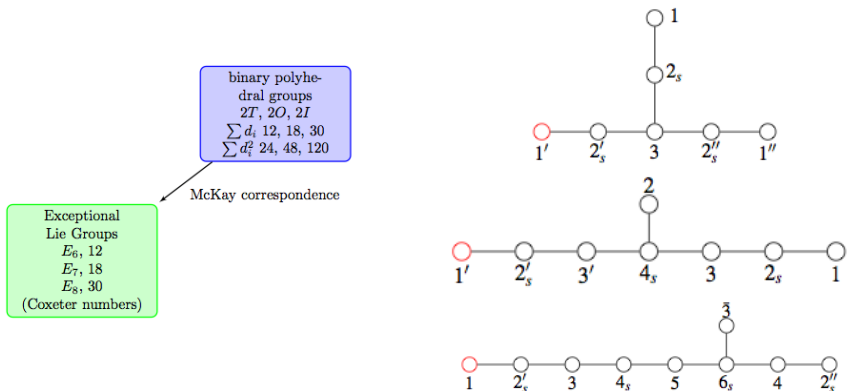
Group	Discrete subgroup	Action Mechanism
$SO(3)$	rotational (chiral)	$x \rightarrow \tilde{R}xR$
$O(3)$	reflection (full/Coxeter)	$x \rightarrow \pm \tilde{A}xA$
$Spin(3)$	binary	$(R_1, R_2) \rightarrow R_1 R_2$
$Pin(3)$	pinor	$(A_1, A_2) \rightarrow A_1 A_2$

- e.g. the **chiral icosahedral** group has 60 elements, encoded in Clifford by 120 spinors, which form the **binary icosahedral** group
- together with the **inversion/pseudoscalar** I this gives 60 rotations and 60 rotoinversions, i.e. the **full icosahedral** group H_3 in 120 elements (with 240 pinors)

Some Group Theory: chiral, full, binary, pin

- Easy enough to calculate **conjugacy classes** etc of pinors in Clifford algebra
- Chiral (**binary**) polyhedral groups have irreps
- tetrahedral (12/24): $1, 1', 1'', 2_s, 2'_s, 2''_s, 3$
- octahedral (24/48): $1, 1', 2, 2_s, 2'_s, 3, 3', 4_s$
- icosahedral (60/120): $1, 2_s, 2'_s, 3, \bar{3}, 4, 4_s, 5, 6_s$
- Binary groups are **discrete subgroups of $SU(2)$** and all thus have a 2_s spinor irrep
- Connection with the **McKay correspondence!**

The McKay Correspondence: Coxeter number, dimensions of irreps and tensor product graphs

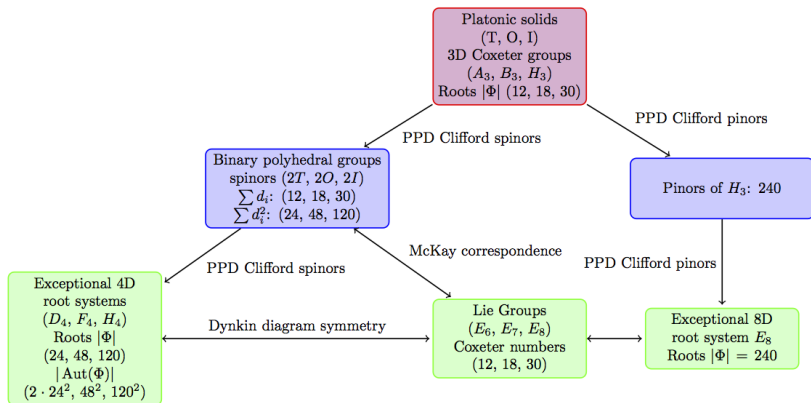


The McKay Correspondence

More than E-type groups: the infinite family of 2D groups, the **binary cyclic** and **dicyclic groups** are in correspondence with A_n and D_n , e.g. the quaternion group Q and D_4^+ . So McKay correspondence not just a trinity but **ADE-classification**. We also have $I_2(n)$ on top of the trinity (A_3, B_3, H_3)

rank-3 group	diagram	binary	rank-4 group	diagram	Lie algebra	diagram
$A_1 \times A_1 \times A_1$		Q	$A_1 \times A_1 \times A_1 \times A_1$		D_4^+	
A_3		$2T$	D_4		E_6^+	
B_3		$2O$	F_4		E_7^+	
H_3		$2I$	H_4		E_8^+	

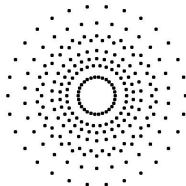
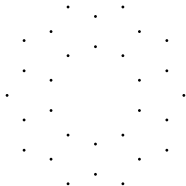
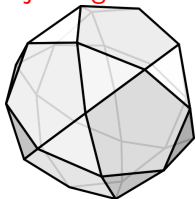
New explicit connections



- 1 Viruses, root systems and affine extensions
 - Viruses
 - Root systems
 - Affine extensions
- 2 Clifford algebras and exceptional root systems
 - Clifford basics
 - E_8 from the icosahedron
 - 3D to 4D spinor induction
 - Trinities and McKay correspondence
- 3 The Coxeter plane

The Coxeter Plane

- Every (for our purposes) Coxeter group has a Coxeter plane.
- A way to visualise Coxeter groups in any dimension by projecting their root system onto the Coxeter plane



Coxeter Elements, Degrees and Exponents

- Like the symmetric group, Coxeter groups can have **invariant polynomials**. Their **degrees** d are important invariants/group characteristics.
- Turns out that actually **degrees** d are intimately related to so-called **exponents** m $m = d - 1$.

Coxeter Elements, Degrees and Exponents

- A **Coxeter Element** is any combination of all the simple reflections $w = s_1 \dots s_n$, i.e. in Clifford algebra it is encoded by the versor $W = \alpha_1 \dots \alpha_n$ acting as $v \rightarrow wv = \pm \tilde{W}vW$. All such elements are conjugate and thus their **order** is invariant and called the **Coxeter number** h .
- The Coxeter element has **complex eigenvalues** of the form $\exp(2\pi mi/h)$ where m are called **exponents**:

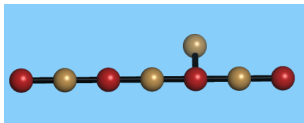
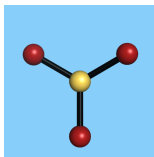
$$wx = \exp(2\pi mi/h)x$$
- Standard theory **complexifies** the real Coxeter group situation in order to find **complex eigenvalues**, then takes **real sections** again.

Coxeter Elements, Degrees and Exponents

- The Coxeter element has **complex eigenvalues** of the form $\exp(2\pi mi/h)$ where m are called **exponents**
- Standard theory **complexifies** the real Coxeter group situation in order to find **complex eigenvalues**, then takes **real** sections again.
- In particular, **1** and **$h-1$** are always exponents
- Turns out that actually **exponents and degrees** are intimately related (**$m = d-1$**). The construction is slightly roundabout but uniform, and uses the **Coxeter plane**.

The Coxeter Plane

- In particular, can show **every** (for our purposes) Coxeter group has a Coxeter plane
- Existence relies on the fact that all groups in question have **tree-like Dynkin diagrams**, and thus admit an **alternate colouring**
- Essentially just gives **two sets of mutually commuting generators**



The Coxeter Plane

- Existence relies on the fact that all groups in question have **tree-like Dynkin diagrams**, and thus admit an alternate colouring
- Essentially just gives **two sets of orthogonal = mutually commuting generators but anticommuting root vectors** α_w and α_b (duals ω)
- Cartan matrices are positive definite, and thus have a **Perron-Frobenius** (all positive) eigenvector λ_i .
- Take **linear combinations** of components of this eigenvector as coefficients of two vectors from the orthogonal sets
$$v_w = \sum \lambda_w \omega_w \text{ and } v_b = \sum \lambda_b \omega_b$$
- Their **outer product/Coxeter plane bivector** $B_C = v_b \wedge v_w$ describes an **invariant plane** where w acts by rotation by $2\pi/h$.

Clifford Algebra and the Coxeter Plane – 2D case

$$I_2(n) \quad \circ \xrightarrow{n} \circ$$

- For $I_2(n)$ take $\alpha_1 = e_1, \alpha_2 = -\cos \frac{\pi}{n} e_1 + \sin \frac{\pi}{n} e_2$

- So **Coxeter versor** is just

$$W = \alpha_1 \alpha_2 = -\cos \frac{\pi}{n} + \sin \frac{\pi}{n} e_1 e_2 = -\exp \left(-\frac{\pi}{n} \right)$$

- In Clifford algebra it is therefore immediately obvious that the action of the $I_2(n)$ Coxeter element is described by a versor (here a rotor/spinor) that encodes **rotations in the $e_1 e_2$ -Coxeter-plane** and yields **$h = n$** since trivially $W^n = (-1)^{n+1}$ yielding $w^n = 1$ via $wv = \tilde{W}vW$.

Clifford Algebra and the Coxeter Plane – 2D case

- So **Coxeter versor** is just $W = -\exp\left(-\frac{\pi I}{n}\right)$
- $I = e_1 e_2$ **anticommutes** with both e_1 and e_2 such that **sandwiching formula** becomes

$$v \rightarrow wv = \tilde{W}vW = \tilde{W}^2v = \exp\left(\pm \frac{2\pi I}{n}\right)v \text{ immediately}$$

yielding the standard result for the **complex eigenvalues** in real Clifford algebra **without any need for artificial complexification**

- The Coxeter plane bivector $B_C = e_1 e_2 = I$ gives the **complex structure**
- The Coxeter plane bivector B_C is invariant under the **Coxeter versor** $\tilde{W}B_CW = \pm B_C$.

Clifford algebra: no need for complexification

- Turns out in Clifford algebra we can **factorise** W into **orthogonal** (commuting/anticommuting) components

$$W = \alpha_1 \dots \alpha_n = W_1 \dots W_n \text{ with } W_i = \exp(\pi m_i l_i / h)$$
- Here, l_i is a bivector describing a **plane** with $l_i^2 = -1$
- For v **orthogonal to the plane** described by l_i we have

$$v \rightarrow \tilde{W}_i v W_i = \tilde{W}_i W_i v = v \text{ so cancels out}$$
- For v **in the plane** we have

$$v \rightarrow \tilde{W}_i v W_i = \tilde{W}_i^2 v = \exp(2\pi m_i l_i / h) v$$
- Thus if we **decompose** W into **orthogonal eigenspaces**, in the eigenvector equation all orthogonal bits cancel out and one gets the complex eigenvalue from the respective eigenspace

Clifford algebra: no need for complexification

- For v in the plane we have

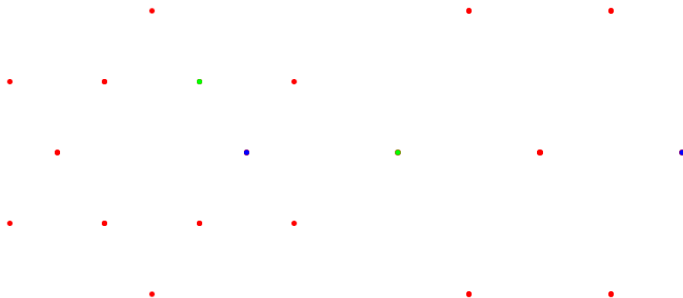
$$v \rightarrow \tilde{W}_i v W_i = \tilde{W}_i^2 v = \exp(2\pi m_i l_i / h) v$$

- So **complex eigenvalue equation** arises geometrically **without any need** for complexification
- Different complex structures** immediately give different **eigenplanes**
- Eigenvalues/angles/**exponents** given from just factorising $W = \alpha_1 \dots \alpha_n$
- E.g. H_4 has exponents 1, 11, 19, 29 and $W = \exp\left(\frac{\pi}{30} B_C\right) \exp\left(\frac{11\pi}{30} I B_C\right)$
- Here we have been looking for orthogonal eigenspaces, so **innocuous** – different complex structures commute
- But not in general – **naive complexification** can be misleading

4D case: D_4

- E.g. D_4 has exponents 1, 3, 3, 5
- Coxeter versor decomposes into **orthogonal components**

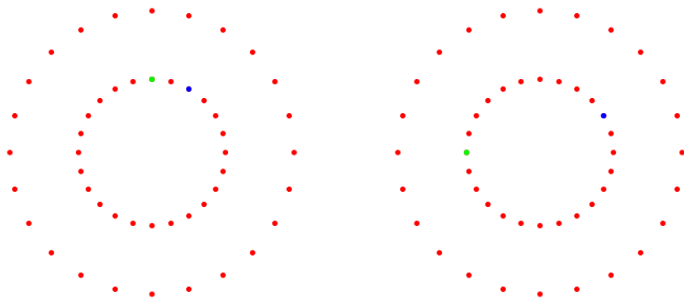
$$W = \alpha_1 \alpha_2 \alpha_3 \alpha_4 = \exp\left(\frac{\pi}{6} B_C\right) \exp\left(\frac{3\pi}{6} I B_C\right)$$



4D case: F_4

- E.g. F_4 has exponents 1, 5, 7, 11
- Coxeter versor decomposes into **orthogonal components**

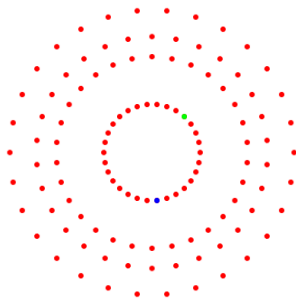
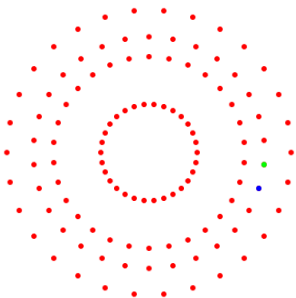
$$W = \alpha_1 \alpha_2 \alpha_3 \alpha_4 = \exp\left(\frac{\pi}{12} B_C\right) \exp\left(\frac{5\pi}{12} I B_C\right)$$



4D case: H_4

- E.g. H_4 has exponents 1, 11, 19, 29
- Coxeter versor decomposes into **orthogonal components**

$$W = \alpha_1 \alpha_2 \alpha_3 \alpha_4 = \exp\left(\frac{\pi}{30} B_C\right) \exp\left(\frac{11\pi}{30} I B_C\right)$$



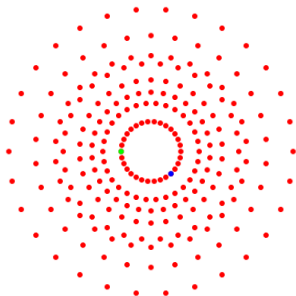
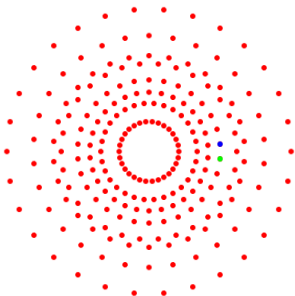
Clifford Algebra and the Coxeter Plane – 4D case summary

rank 4	exponents	W-factorisation
A_4	1, 2, 3, 4	$W = \exp\left(\frac{\pi}{5} B_C\right) \exp\left(\frac{2\pi}{5} I B_C\right)$
B_4	1, 3, 5, 7	$W = \exp\left(\frac{\pi}{8} B_C\right) \exp\left(\frac{3\pi}{8} I B_C\right)$
D_4	1, 3, 3, 5	$W = \exp\left(\frac{\pi}{6} B_C\right) \exp\left(\frac{\pi}{2} I B_C\right)$
F_4	1, 5, 7, 11	$W = \exp\left(\frac{\pi}{12} B_C\right) \exp\left(\frac{5\pi}{12} I B_C\right)$
H_4	1, 11, 19, 29	$W = \exp\left(\frac{\pi}{30} B_C\right) \exp\left(\frac{11\pi}{30} I B_C\right)$

8D case: E_8

- E.g. H_4 has exponents 1, 11, 19, 29, E_8 has 1, 7, 11, 13, 17, 19, 23, 29
- Coxeter versor decomposes into **orthogonal components**

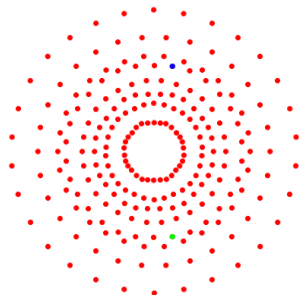
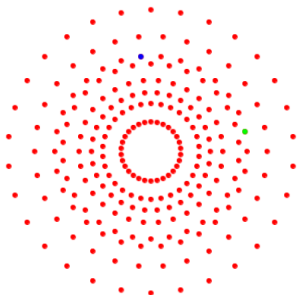
$$W = \alpha_1 \dots \alpha_8 = \exp\left(\frac{\pi}{30} B_C\right) \exp\left(\frac{7\pi}{30} B_2\right) \exp\left(\frac{11\pi}{30} B_3\right) \exp\left(\frac{13\pi}{30} B_4\right)$$



8D case: E_8

- E.g. H_4 has exponents 1, 11, 19, 29, E_8 has 1, 7, 11, 13, 17, 19, 23, 29
- Coxeter versor decomposes into **orthogonal components**

$$W = \alpha_1 \dots \alpha_8 = \exp\left(\frac{\pi}{30} B_C\right) \exp\left(\frac{7\pi}{30} B_2\right) \exp\left(\frac{11\pi}{30} B_3\right) \exp\left(\frac{13\pi}{30} B_4\right)$$



Imaginary differences – different imaginaries

So what has been **gained** by this **Clifford view**?

- There are **different** entities that serve as **unit imaginaries**
- They have a **geometric** interpretation as an **eigenplane of the Coxeter element**
- These don't need to **commute** with everything like i (though they do here – at least anticommute. But that is because we looked for **orthogonal decompositions**)
- But see that in general **naive complexification** can be a dangerous thing to do – **unnecessary**, issues of **commutativity**, **confusing** different imaginaries etc

The countably infinite family $I_2(n)$ and ADE

- For A_1^3 can see immediately $8 = 2(1 + 1 + 1 + 1)$
- Simple roots $\alpha_1 = e_1, \alpha_2 = e_2, \alpha_3 = e_3, \alpha_4 = e_4$ give
$$W = e_1 e_2 e_3 e_4 = \left(\cos \frac{\pi}{2} + \sin \frac{\pi}{2} e_1 e_2\right) \left(\cos \frac{\pi}{2} + \sin \frac{\pi}{2} e_3 e_4\right) = \exp\left(\frac{\pi}{2} e_1 e_2\right) \exp\left(\frac{\pi}{2} e_3 e_4\right)$$
- Gives exponents $(1, 1, 1, 1) (2 - 1)$

The countably infinite family $I_2(n)$ and ADE

- For $A_1 \times I_2(n)$ one gets the same decomposition
 $4n = 2(1 + (n-1) + 1 + (n-1)) = 2 \cdot 2n$
- Simple roots $\alpha_1 = e_1$, $\alpha_2 = -\cos \frac{\pi}{n} e_1 + \sin \frac{\pi}{n} e_2$, $\alpha_3 = e_3$,
 $\alpha_4 = -\cos \frac{\pi}{n} e_3 + \sin \frac{\pi}{n} e_4$ give $W = \exp\left(-\frac{\pi e_1 e_2}{n}\right) \exp\left(-\frac{\pi e_3 e_4}{n}\right)$
- Gives exponents $(1, (n-1), 1, (n-1))$

The countably infinite family $I_2(n)$ and ADE

- So Arnold's initial hunch regarding the exponents **extends in fact to my full correspondence**
- **McKay correspondence** is a correspondence between even subgroups of $SU(2)/\text{quaternions}$ and ADE affine Lie algebras
- In fact here get the even quaternion subgroups from 3D – **link to ADE affine Lie algebras** via McKay?

The countably infinite family $I_2(n)$, finite subgroups of $SU(2)$ and ADE

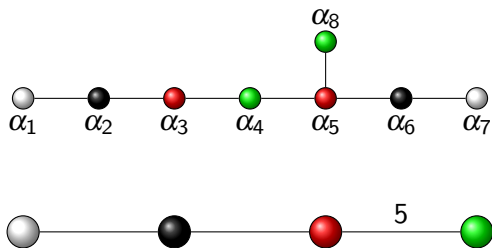
- Double cover of cyclic group of order n (**binary cyclic group** is $I_2(n)$ as a root system – corresponding to **A_n affine Lie algebras** (2D root systems are self-dual – just see complex part)
- The **dicyclic group**/binary dihedral group is $I_2(n) \times I_2(n)$ – corresponding to **D_n affine Lie algebras**
- The **binary tetrahedral, octahedral and icosahedral** groups are **D_4 , F_4 and H_4** as root systems – and correspond to **E-type Lie algebras E_6 , E_7 , E_8**
- Get **all of the even subgroups of the quaternions** from 2D and 3D root systems and via McKay correspondence the ADE Lie algebras
- Is there a **direct correspondence** between the root systems and

Conclusions

- **All exceptional** geometries arise in **3D**, root systems giving rise to Lie groups/algebras etc
- Completely novel **spinorial** way of viewing **exceptional** geometries as 3D phenomena – implications for HEP etc?
- New view of Coxeter **degrees and exponents** with **geometric interpretation of imaginaries**
- A unified framework for doing **group and representation theory**: polyhedral, orthogonal, conformal, modular (Moonshine) etc
- Correspondence between 3D & 4D root systems (and perhaps 2D) extends to full **ADE correspondence** with McKay and **generalising Arnold's link between trinities** via 3D Weyl chamber decomposition and **exponents** in the 4D Coxeter plane

Thank you!

Projection and Diagram Foldings



$$s_{\beta_1} = s_{\alpha_1} s_{\alpha_7}, \quad s_{\beta_2} = s_{\alpha_2} s_{\alpha_6}, \quad s_{\beta_3} = s_{\alpha_3} s_{\alpha_5}, \quad s_{\beta_4} = s_{\alpha_4} s_{\alpha_8} \Rightarrow H_4$$

- E_8 has a H_4 subgroup of **rotations** via a 'partial folding'
- Can **project** 240 E_8 roots to $H_4 + \tau H_4$ – essentially the **reverse** of the previous construction!
- **Coxeter element & number** of E_8 and H_4 are the **same**

4D geometry is surprisingly important for HEP

- 4D root systems are **surprisingly relevant to HEP**
- A_4 is $SU(5)$ and comes up in **Grand Unification**
- D_4 is $SO(8)$ and is the little group of **String theory**
- In particular, its **triality symmetry** is crucial for showing the equivalence of RNS and GS strings
- B_4 is $SO(9)$ and is the little group of **M-Theory**
- F_4 is the **largest crystallographic** symmetry in 4D and H_4 is the **largest non-crystallographic** group
- The above are **subgroups** of the latter two
- **Spinorial nature** of the root systems could have **surprising consequences for HEP**